

KSC Weather and Research

An artist's rendering of the Space Launch System (SLS) rocket ascending through a dense layer of clouds. The rocket is shown as a dark, slender column with a bright, glowing tip at its nose, indicating the point of maximum heat and light during ascent. The clouds are depicted in shades of orange, yellow, and brown, suggesting a sunrise or sunset scene. The sky above the clouds is a clear, pale blue.

NASA Kennedy Space Center

Launa Maier
Dr. Lisa Huddleston
Kristin Smith

January 27, 2016

*Artist rendering of SLS
soaring through clouds*

- Background
- Past Research
- KSC Weather Today, Staff, Responsibilities, Activities
- Evolution of Weather Support
- Future Technology
- Buoy Update
- Summary





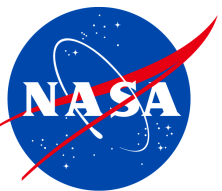
Background



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- Prior and during Apollo, the Weather Bureau (later named the National Weather Service) provided meteorological support for Kennedy Space Center (KSC) and had offices at Johnson Space Center (JSC), Miami, Honolulu and Washington D.C.
 - During this time, the USAF provided some meteorological services including rawinsondes, weather radar, surface-based instruments and a network of wind towers for diffusion of toxic/nuclear materials. (ref. KCA-1645 Webb-McNamara Agreement)
- Post Apollo, KSC elected to use the USAF for weather support and JSC continued to use the National Weather Service.
- The Lightning Advisory Panel (LAP) was formed following investigation of triggered lightning event on launch (AC-67) to provide rules and associated technical rationale for launch constraints to preclude triggered lightning during launch.
- Weather Office formed about the same time, based upon recommendation of the investigation board.
- The Weather Support Office (WSO) was formed at NASA HQ about the same time. Subsequently, (late 90s) this responsibility was delegated to John Madura at KSC and the WSO was eliminated.
- Shortly thereafter, the Applied Meteorology Unit was formed based upon recommendations from NASA-sponsored panel to develop and apply new measurement technology as well as new weather analysis and fore-casting techniques to improve weather support for space operations.



Thunderstorm Research International Program (TRIP)

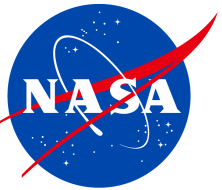


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- South Dakota School of Mines T-28 (1978)
- NASA-6 Airborne Field Mill
- New Mexico Tech Rain Gauges (Brook)
- Environmental Research Laboratory C-131 (Kasemir)
- Kennedy Space Center NASA-6 (Taiani)
- Naval Research Laboratories S2D (Ruhnke)
- University of Arizona (Krider)
- Rice University (Few)
- Transportation Systems Center (Kalafus)
- AF Flight Dynamics Laboratory (Baum)
- JSC (Arabian)
- GSFC (LeVine)
- Stanford Research Institute (Nanevicz)
- Statue University of New York at Albany (Orville and Idone)
- Pennsylvania State University (Panofsky)
- National Severe Storms Laboratory (Rust and Taylor)
- USAF 1035th Technical Operations Group (Turman)
- University of Florida (Uman)
- KSC (Lennon, Poehler, Stubbs, PRC/ Stahmann)

1976-77 TRIP report <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19780003695.pdf>

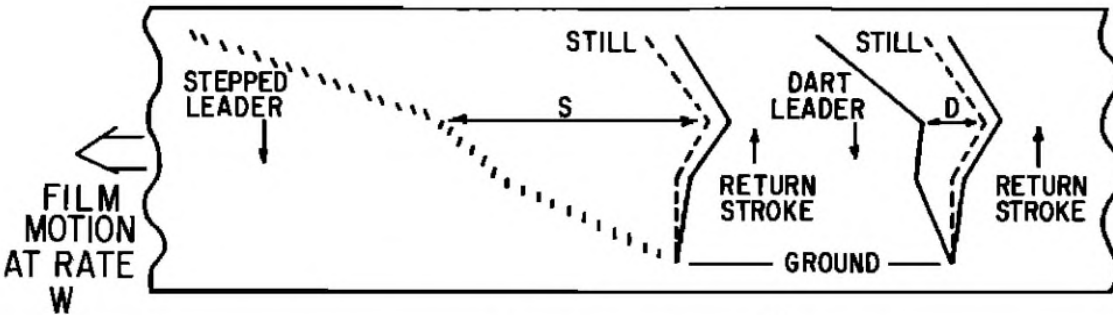
1976 Flight Data https://archive.org/stream/nasa_techdoc_19780025750/19780025750#page/n179/mode/2up



Results from TRIP

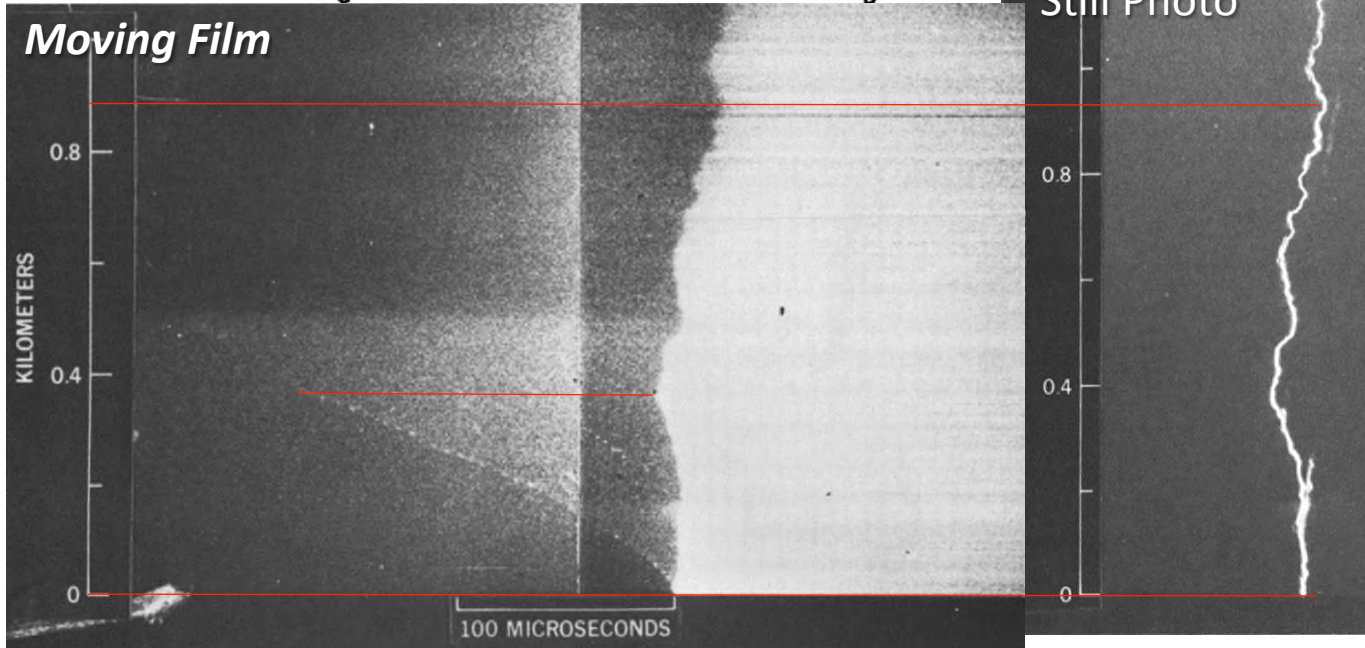


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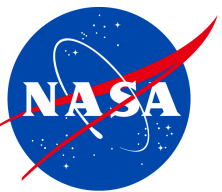


Flash that occurred at 2024:50 UT,
7/29/78, KSC, Florida from
[Orville and Idone](#), JGR, 1982

$$T_s = S/W \quad \text{TIME} \quad T_D = D/W$$



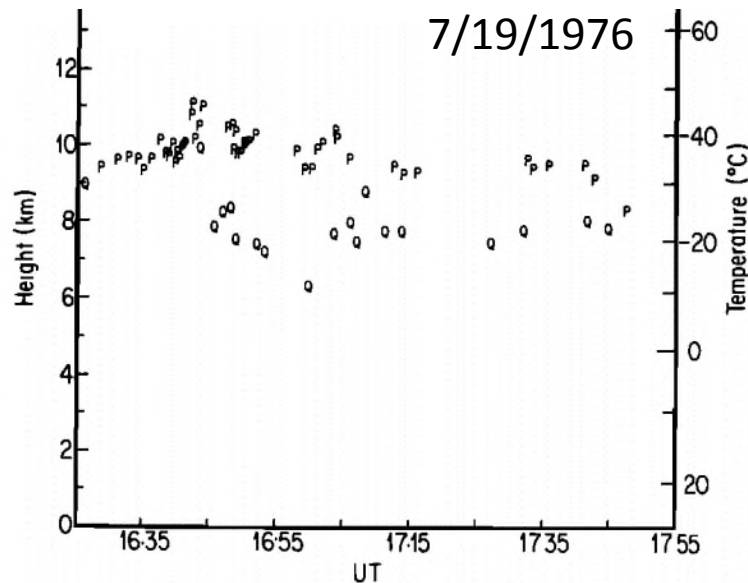
Lightning elements	Velocities
Stepped leaders	2×10^5
Dart-stepped leaders	$1-2 \times 10^6$
Dart leaders	$1-2 \times 10^7$
Return Strokes	$2 \times 10^7 - 2.8 \times 10^8$
IX International Symposium on Lightning Protection, Rakov, 2007	



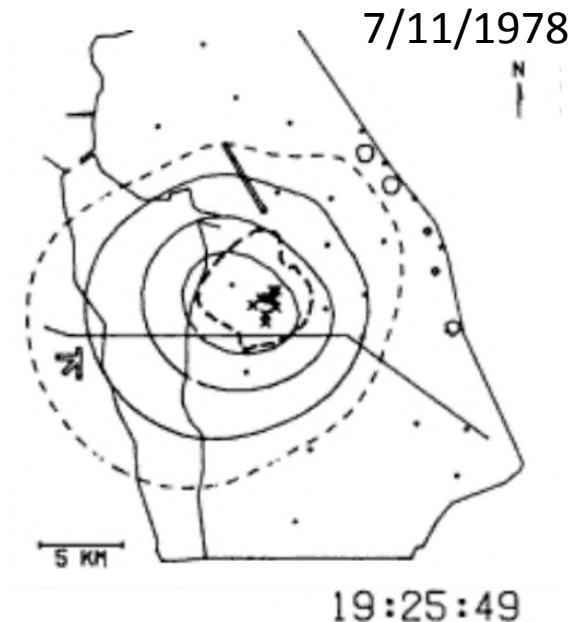
Locating Lightning and Thunderstorm Currents with Electric Field Mills



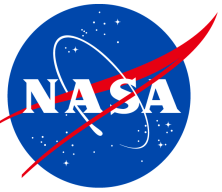
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Altitudes of charges deposited by cloud-to-ground lightning and use of dipoles to locate intracloud lightning, Maier and Krider, JGR, 1986



The Electric Currents Produced by Thunderstorms, Krider and Blakeslee, J. Electrostatics, 1985



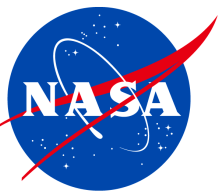
Rocket-Triggered Lightning



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- NASA hosted the Rocket-triggered lightning program from 1984-1991
- Repeatedly triggered lightning at a known location to measure lightning characteristics
- Researchers from France, Florida, New York, Arizona and more participated in characterizing the currents, velocities, spectrums, etc. of triggered lightning



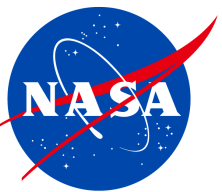
Lightning Protection Systems



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- Numerous systems are employed to protect sensitive hardware from lightning effects
- These systems have also been used to study the characteristics of lightning; e.g., frequency of occurrence, return strokes, currents, induced currents, and more
- Systems used include catenary wire system, lightning towers, internal electric measurements to quantify induced voltages, electric and magnetic field measurements and more

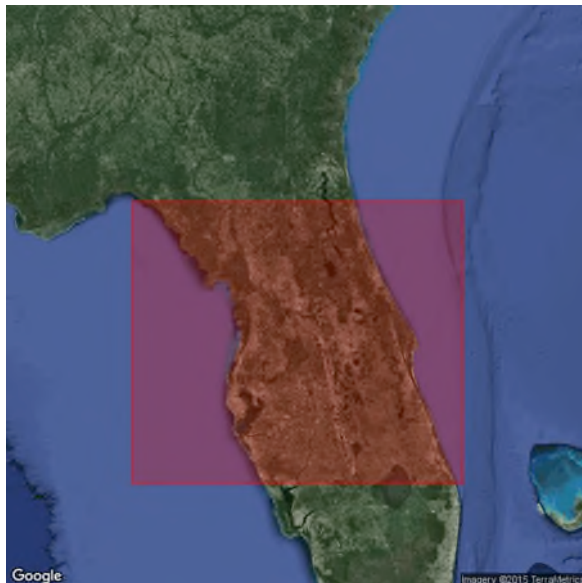


Convection and Precipitation Experiment (CaPE)



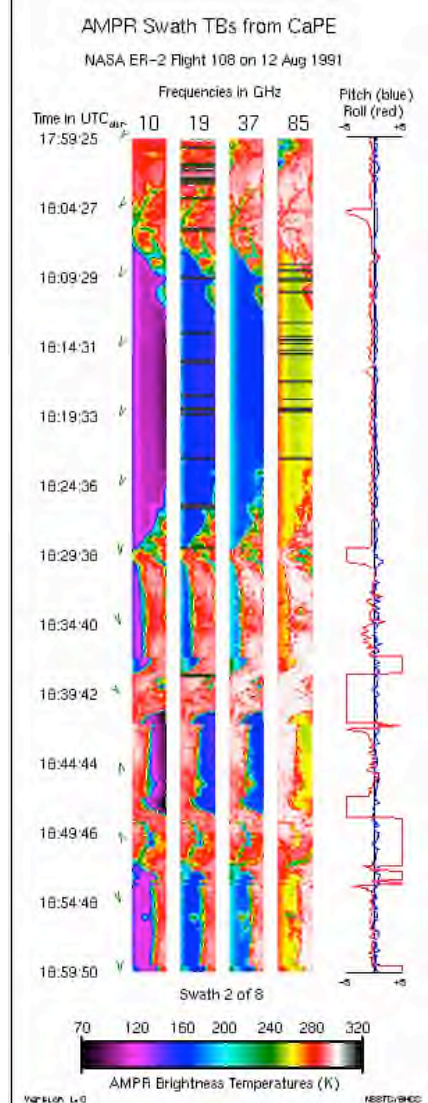
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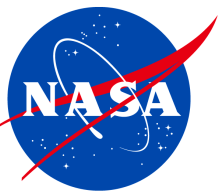
- The Convection and Precipitation/Electrification Experiment (CaPE)
 - 7/18-8/18, 1991
 - Participants included NSF, FAA, NASA, NOAA, USAF
 - Main Objectives: 1) Relationship between wind, water and electric fields in convective clouds; 2) Mesoscale model forecasts of wind, cloud and thunderstorms; 3) Improving nowcasting of convection, downbursts and tornadoes; 4) precipitation particle characterization and estimation of rainfall



Example Experiment: The Advanced Microwave Precipitation Radiometer

The AMPR is a total power passive microwave radiometer producing calibrated brightness temperatures (TB) at 10.7, 19.35, 37.1, and 85.5 GHz. These frequencies are sensitive to the emission and scattering of precipitation-size ice, liquid water, and water vapor.





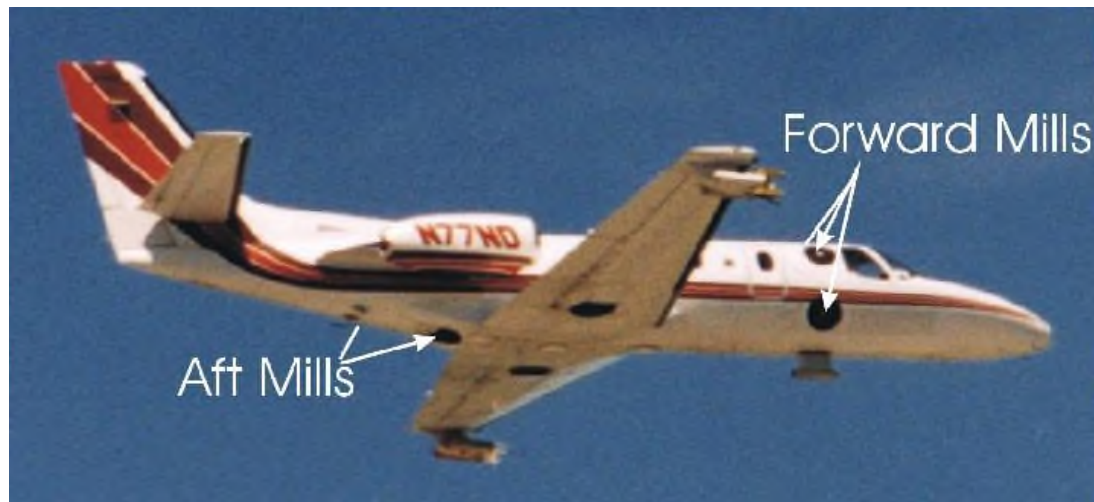
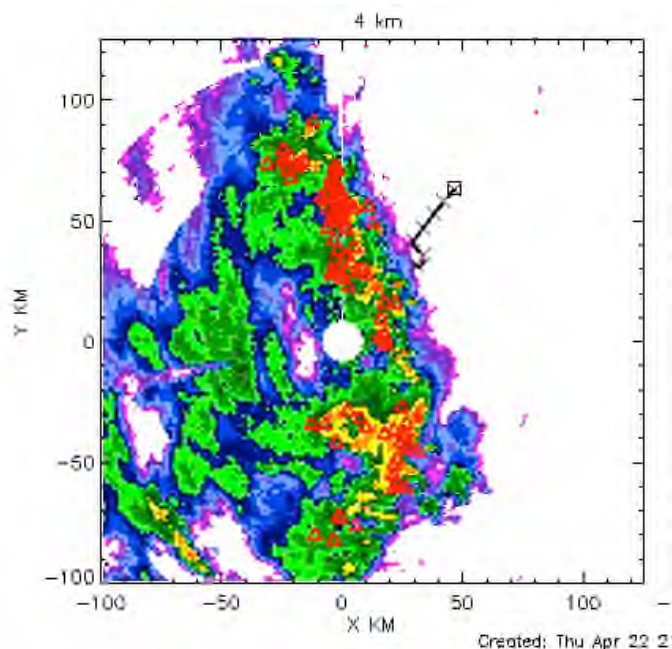
Airborne Field Mill Campaigns



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Airborne Field Mill II (6/2000, 2/2001, 5-6/2001)

- KSC, MSFC, USAF, NCAR, Univ of N Dakota, NHL and NOAA Envir. Tech Lab
- Studied the electric field in anvil and debris clouds



Airborne Field Mill I (2000-2001)

- NASA (HQ, KSC, MSFC, LaRC), USAF, SRI, Aerojet
- Studied the electric field above growing cumulus and inside various cloud types

Purpose: To identify, by measurable parameters, which clouds have sufficient electric field to trigger lightning during launch.

KSC Weather

Lisa Huddleston, AMU Chief

- BS (Industrial Engineering)
- MS (Engineering Management)
- PhD (Environmental Science)
- 12 years NASA; 17 years contractor
- 15+ professional publications



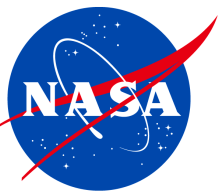
Kristin Smith

- BS (Meteorology)
- MS (Atmospheric & Oceanic Science)
- PhD student (Atmospheric & Oceanic Science)
- 3 years with NASA/KSC, MSFC contractor (2 years)
- 3+ professional publications

Launa Maier, Manager

- BS (Physics)
- MS (Atmospheric Physics)
- MS (Engineering Management)
- NSSL (2 years), Univ Ariz (5 years), CSC (2 years) and NASA (27 years)
- 15+ professional publications





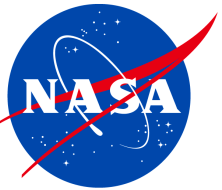
KSC Weather Responsibilities



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- Ensure efficient and effective operational weather support for NASA Programs and Projects
 - Budget and acquire operational weather services (USAF, NDBC, contractor support, etc.)
 - Daily forecasts, warnings (severe weather, lightning, high winds, temperature extremes), access to data
 - Develop both policy and agreements and oversee implementation
 - Develop measurable launch commit criteria to preclude natural or triggered lightning during launch and avoid tribo-electrification hazards
 - Develop and implement sensors, tools, or processes to increase safety of operations and launch and to increase operational and launch availability through relationships with other NASA Centers, USAF and academia
 - Support decision makers in preparations and response to adverse weather events (e.g., tropical weather)
- Provide analysis of weather events for damage assessments and decisions regarding repair, retest and reuse
- Provide priorities for KSC weather research projects to improve operational and launch availability through new tools and techniques (e.g., priorities for SBIR, NASA grants)





KSC Weather Customers



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- Ground Systems and Development Operations, Orion and Space Launch Systems
- 21st Century Ground Systems
- Launch Services Program
- Commercial Crew Program
- Commercial Launchers
- Smaller project such as Advanced Exploration Systems, Lunar Express, Morpheus, Rocket University
- KSC Employees





Weather Partnerships



KSC (50 MHz DRWP, 39B Wx Instr)



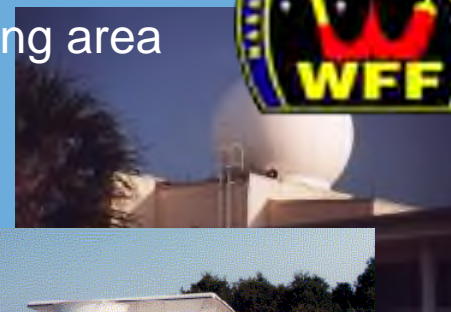
MSFC Natural Environments
Branch (Wx effects on Vehicles)



JSC/NWS (Landing/
Recovery Operations)

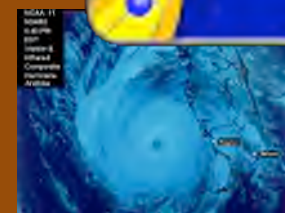


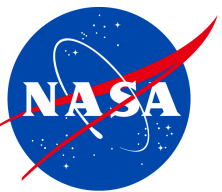
USAF Eastern Range & USAF O&M, Sustaining Contractor
Instruments located at CCAFS, KSC and surrounding area



NOAA NWS Doppler Radar, Satellites, Forecast Models

NOAA NHC Models and Forecasts





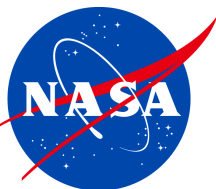
45th Weather Squadron Support to KSC



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- Dedicated Launch Weather Officer (LWO) to provide daily operational forecasts, to support daily operations (e.g., flight hardware moves), to support launch operations and to provide real-time requests for information
- Provides all weather instrumentation (e.g., rawinsondes, weather radar, wind tower network, lightning systems, field mill network, 915 MHz DRWPs) with the exception of the Doppler Radar Wind Profiler (DRWP) and Pad B weather instrumentation used for daily and launch operations
- Provides warnings (e.g., high winds, lightning, tornado, hail, extreme temperature, tropical storm)
- Provides forecasts for weather sensitive operations (e.g., hardware moves, launches, construction, fueling, controlled burns)
- Provides post-event weather data and analyses

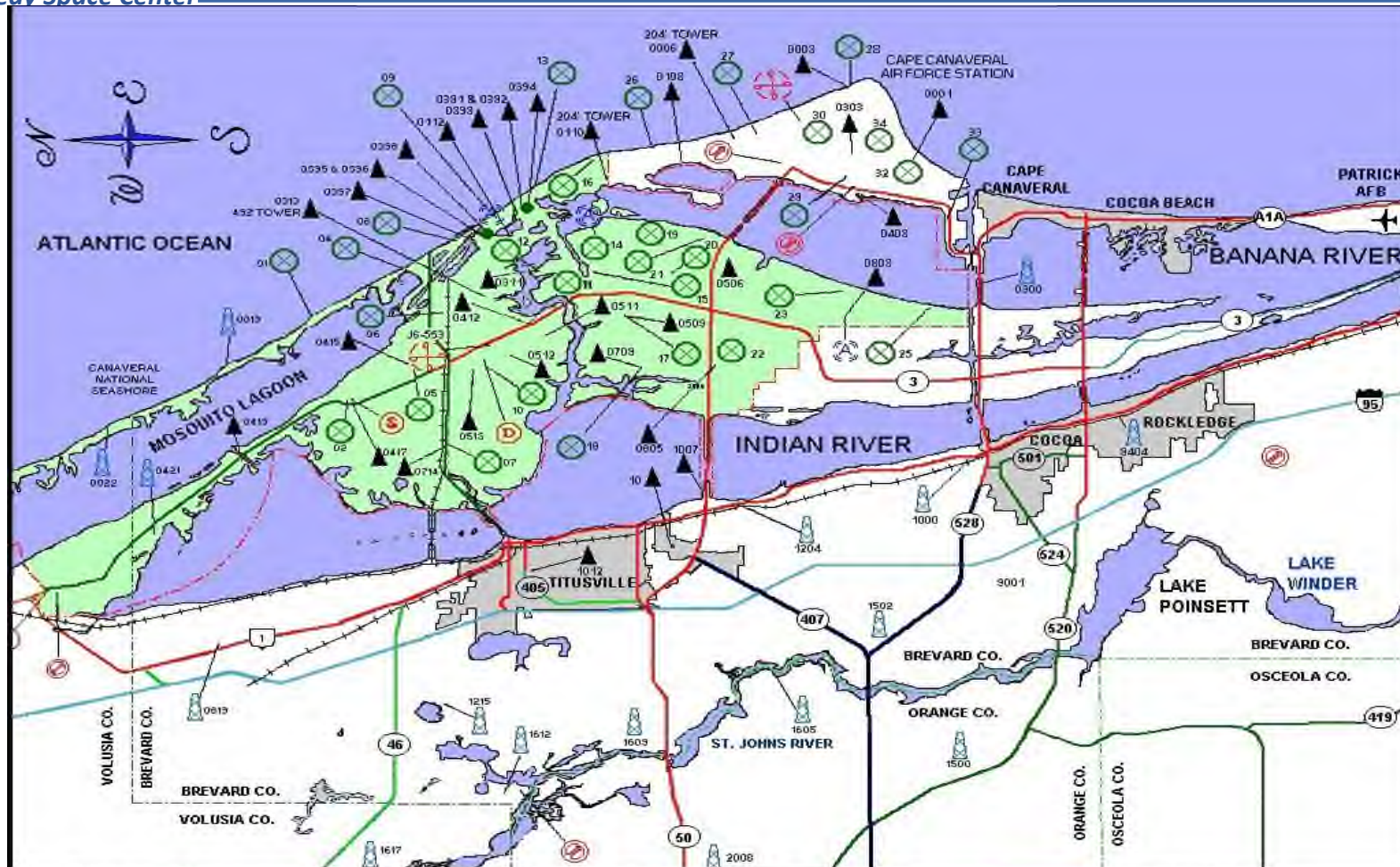




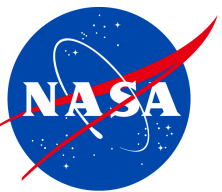
Weather Instrumentation supporting USAF/KSC



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- LEGEND:**
- FIELD MILL
 - MESONET SITE
 - WIND TOWER
 - LLP DIRECTION FINDERS
 - NASCOM MICROWAVE AND S BAND RADAR
 - DOPPLER RADAR WIND PROFILER & TACAN
 - WEATHER STATION
 - ACCOUSTIC SOUNDER
 - KSC PROPERTY
 - RAILROAD
 - TWO LANE ROAD
 - FOUR LANE ROAD
 - CONTROLLED ACCESS ROAD
 - SHORELINE

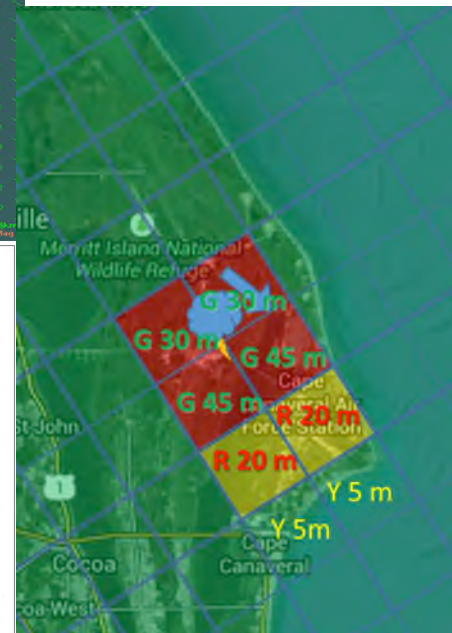
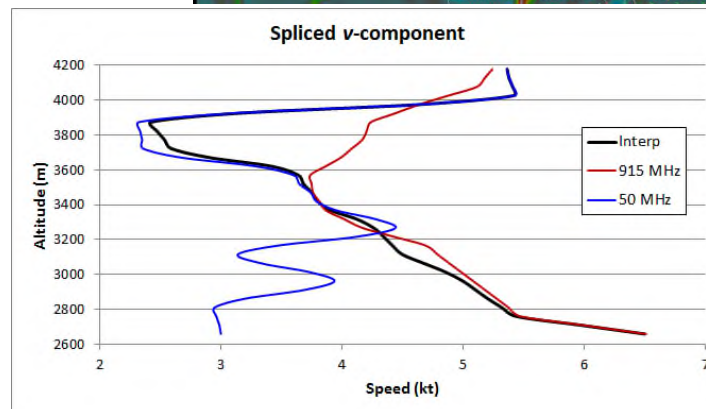
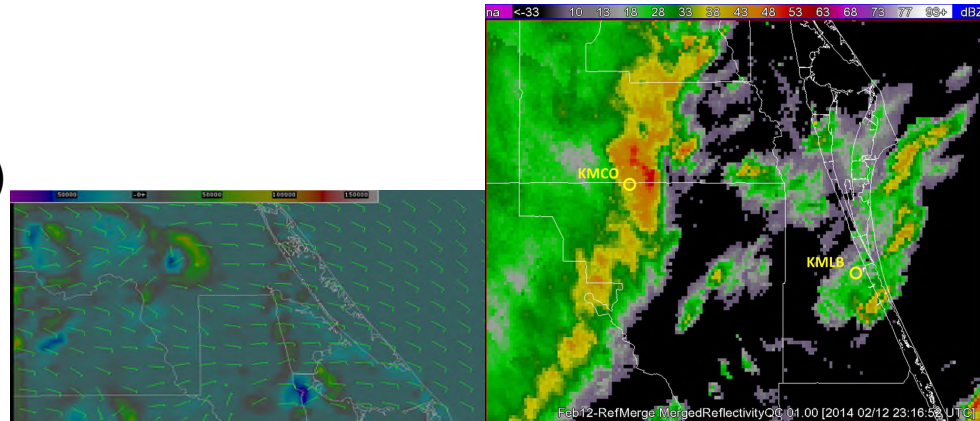


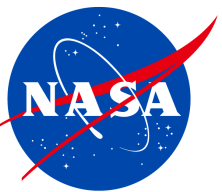
Applied Meteorology Unit



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- Develop and apply new measurement technology (e.g., set up hardware to display wind field from 3 Doppler weather radars, splicing tool for towers, 915 and 50 MHz DRWP)
- Develop and apply new weather analysis and recent forecasting techniques (e.g., localized models for initial convection and fog, validation of DRWP data)
- Improve weather support for space operations by development of overlays and displays specific to customer weather requirements (e.g., range rings for KSC, wind limit displays, anvil movement and timing overlay for LLCC forecasting, video line of sight areas)
- Provide forecaster education and training





Example AMU product: Evaluate Prediction of Local Sea Breeze Fronts from AMU-WRF Model



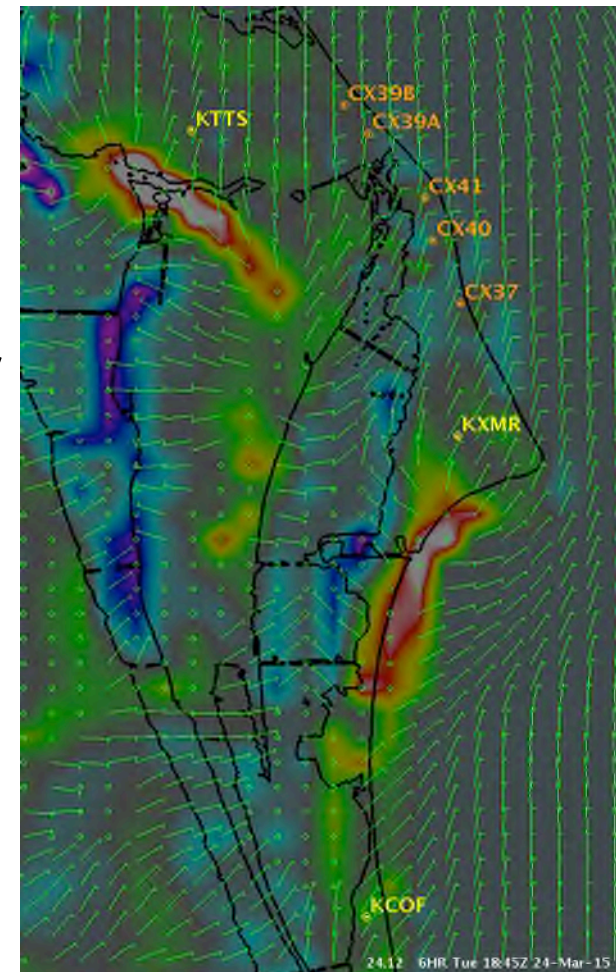
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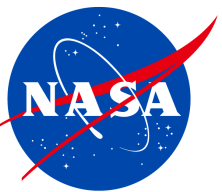
- **Purpose**

- Evaluate performance of the 1.33 km resolution AMU-WRF model in predicting the onset time, inland position, and intensity of sea breeze fronts in the KSC/CCAFS area during the warm season.
- Evaluation will help determine model's ability to predict "first lightning" of the day.

- **Operational Product**

- AMU-WRF model displayed in the Advanced Weather Interactive Processing System (AWIPS) in the AMU and Range Weather Operations.





Example AMU product: Configuration and Evaluation of a Real-Time Dual-Doppler Wind Field System



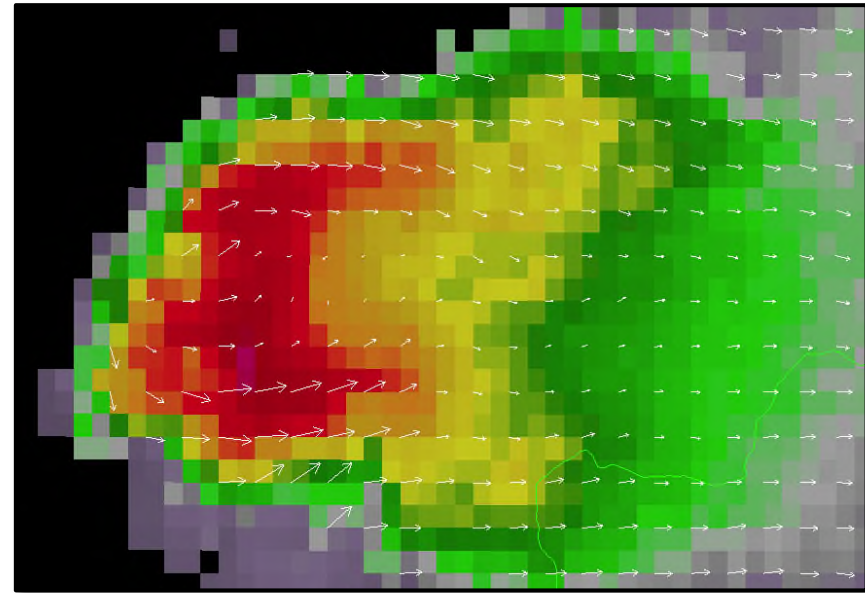
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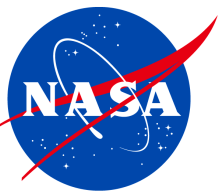
- **Purpose**

- Use radial velocities from two Doppler radars to produce wind fields in real time
- Improve weather model forecasts
- Make horizontal wind field easier to interpret, enabling forecasters to
 - Predict storm development
 - Issue wind and lightning warnings

- **Operational Product**

- Operational version of dual-Doppler software running in real time
- Report of findings from investigation of methods, hardware/software requirements





Example AMU product: Anvil Tool



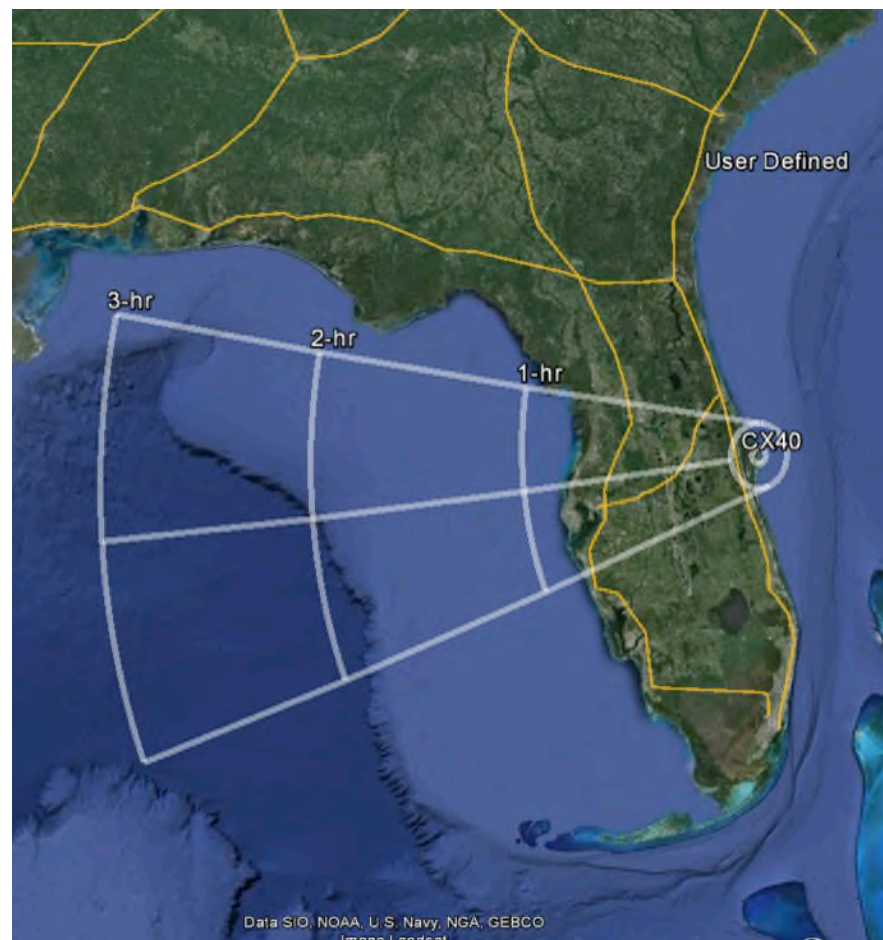
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- **Purpose**

- Predict arrival time of anvil clouds (using upper air wind data from rawinsondes, Doppler radar wind profiler or models)
- Clouds can be a threat for triggered lightning during launch vehicle ascent

- **Operational Product**

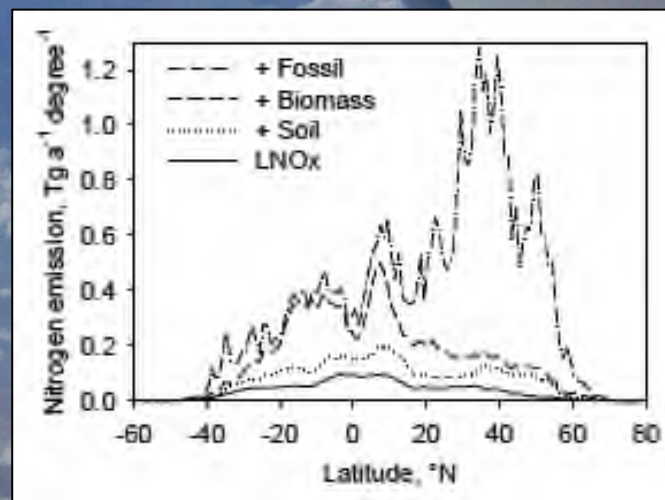
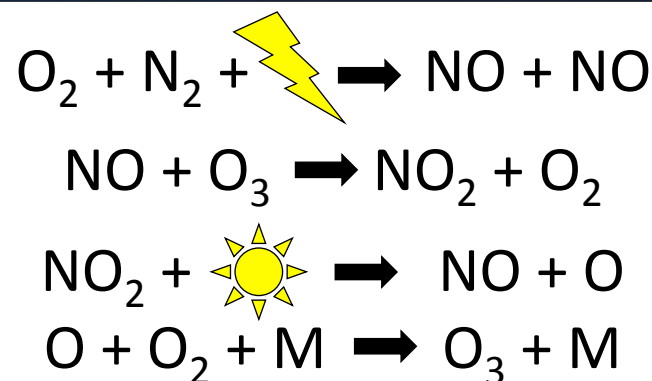
- Centered on launch pad, depict arcs which represent time for clouds to propagate over the launch pad
- Forecast likelihood of constraint violation for upcoming time of launch



Lightning & Chemistry

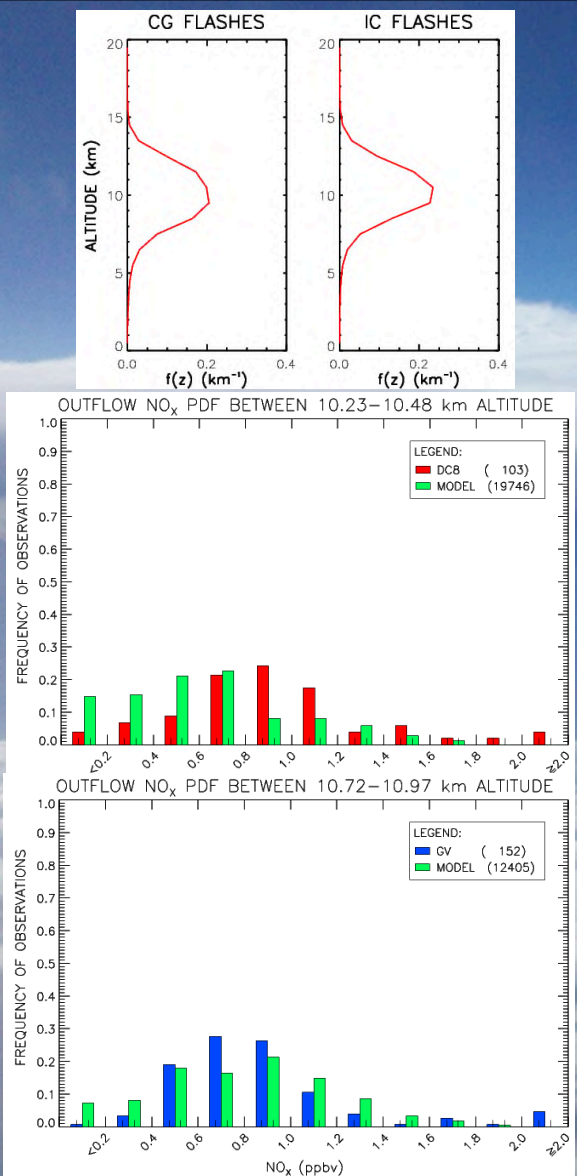


- Largest source of NO_x ($\text{NO} + \text{NO}_2$) in the upper troposphere
- NO_x influences:
 - O_3 production
 - OH concentration
 - Indirectly affects climate
- Roughly 60% uncertainty in amount of lightning-generated NO_x (LNO_x) production
 - Flash type and length
 - Need to better understand for modeling
- How do we reduce uncertainty?
 - Field campaigns
 - Modeling
 - Laboratory tests



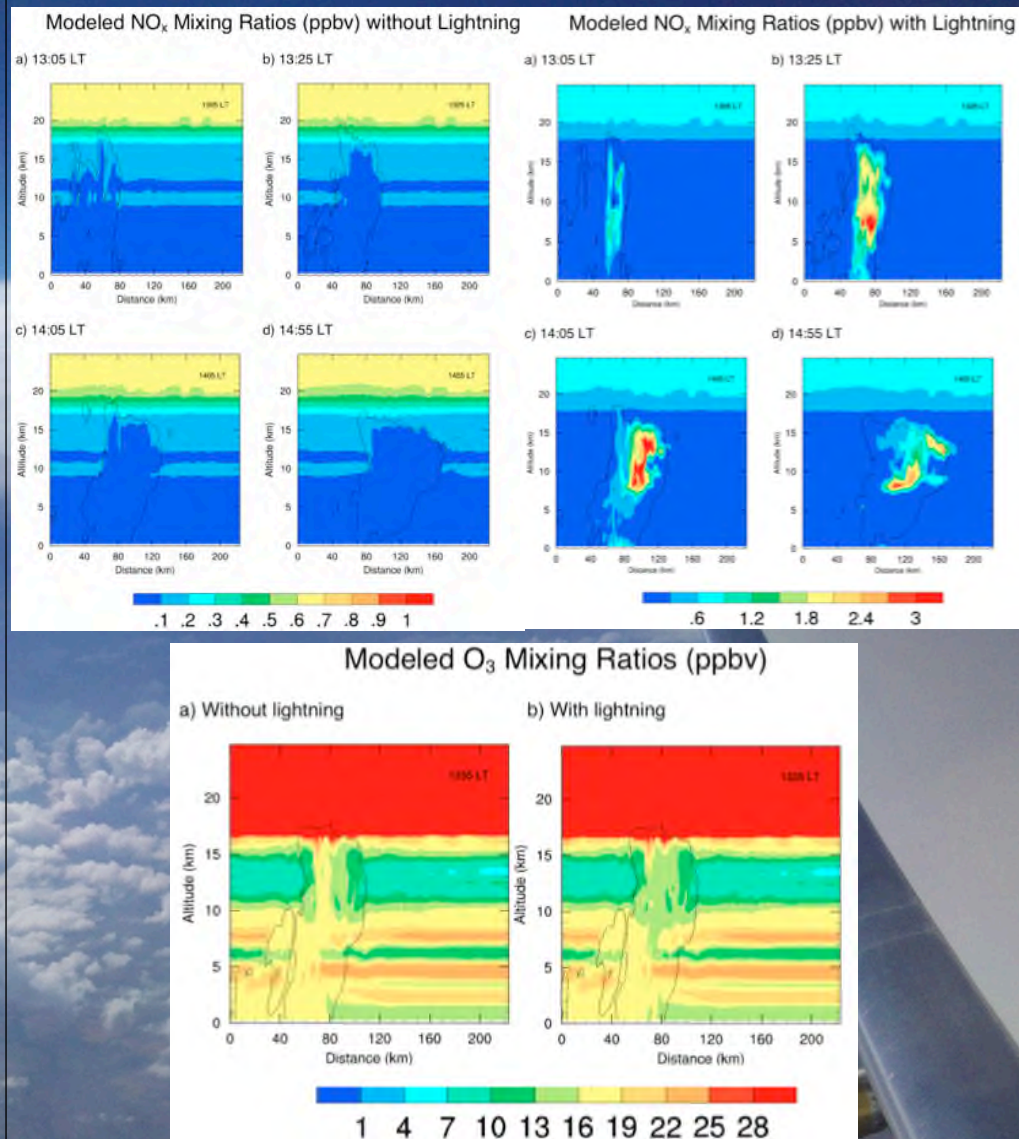
Schumann & Huntrieser, 2007

29 May 2012 Oklahoma Convection (DC3 field campaign)

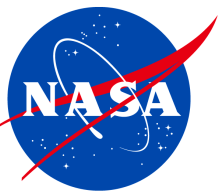


Cummings et al., 2016

16 Nov 2005 Hector Thunderstorm (Darwin, AU; SCOUT-O3/ACTIVE field campaign)



Cummings et al., 2013

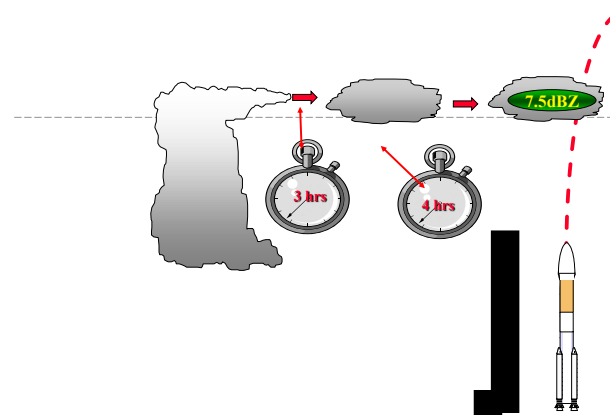
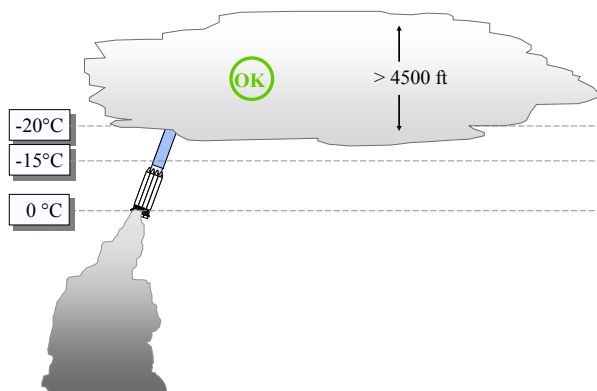


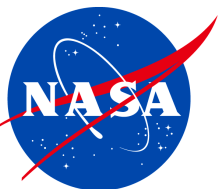
Lightning Advisory Panel



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- Small procurements with world-wide experts to:
 - Develop and update Lightning Launch Commit Criteria (LLCC) to enable safe launch, improve launch availability and document the rationale
 - Advise on lightning advisory and warning criteria, sensors and evaluation technology for improved operational availability
- LLCC utilized for all launch vehicles at all launch sites (i.e., USAF, NASA, and FAA-licensed)

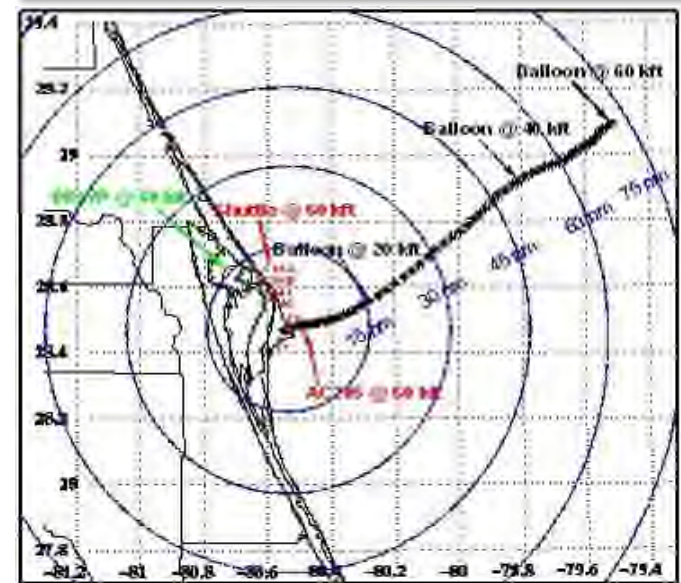
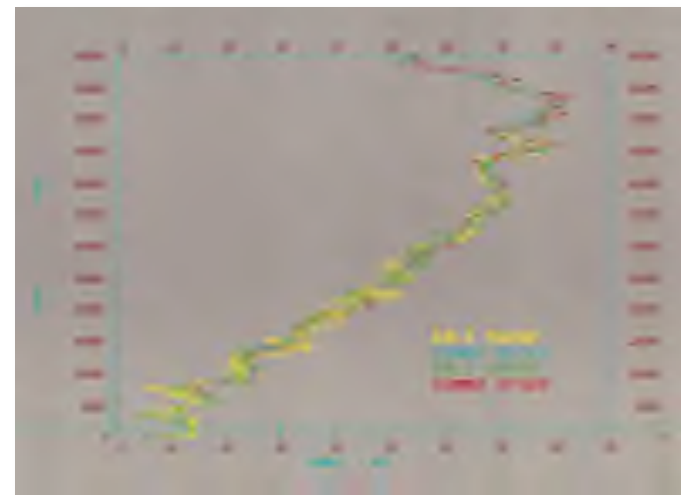




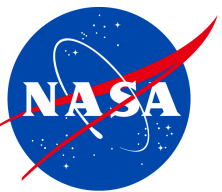
Doppler Radar Wind Profiler



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Operations and maintenance of a phased-array radar comprised of 640 antennas on ~5 acres with solid-state antenna beam-pointing technology to direct a 250 kWatt Doppler beam



50-MHz Doppler Radar Wind Profiler (DRWP)

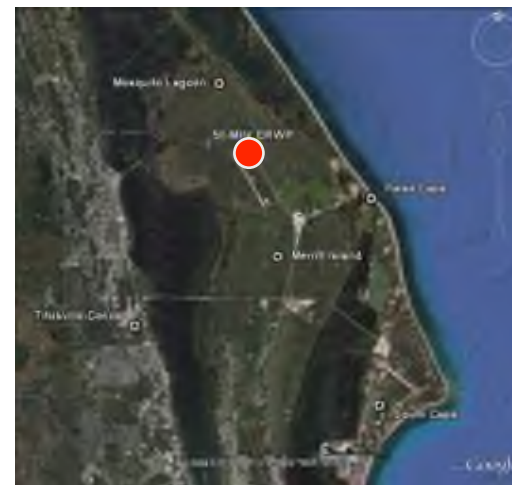


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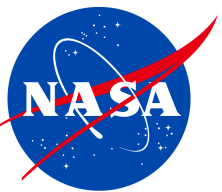
- 50 DRWP: Tropospheric wind profiler
 - Vertical profiles of wind (2,600-18,600 m, every 145 m)
 - Evaluate aerodynamic loading of space launch vehicles
 - Weather balloons take ~1.5 hours to reach top altitude and can drift up to 200 miles downwind
 - 50DRWP is every 3 min and directly overhead



50 MHz DRWP antenna field



50DRWP location



Launch Pad Lightning Warning System (LPLWS)

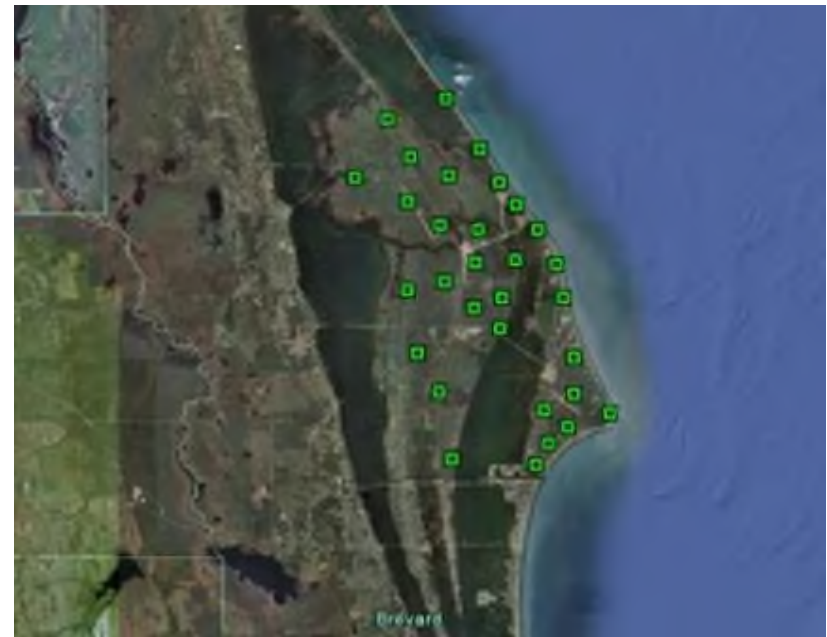


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- 31 surface electric field sensors
 - Electric charge at surface induced by charges aloft
- Evaluate Lightning Launch Commit Criteria
 - Can indicate danger or provide relief from other rules



LPLWS sensor



LPLWS sensor locations

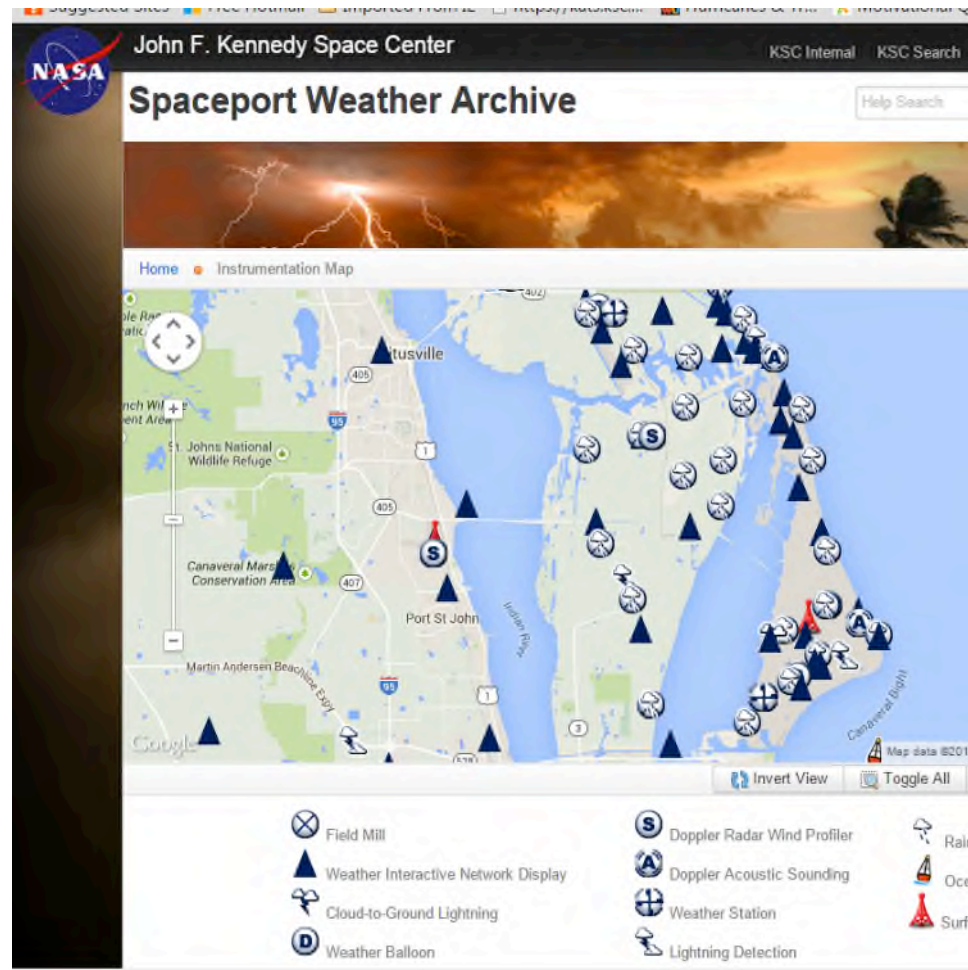


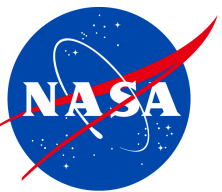
Weather Data Archive



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- Provide timely notification of possible damage to GSE and flight, and spacecraft hardware due to 24/7 near real-time lightning alerts
- Support statistical analyses of weather data necessary for the design of new ground processing, launch, flight, and recovery hardware or facilities
- Provide access to data for investigating weather-related accidents or anomalies
- Provides KSC access to Range Meteorological data which requires a license agreement. This service maintains security and eliminates expense of buying multiple licenses to access data. Provides Range and others access to KSC data.
- Automated scripts which eliminates recurring work; i.e., subsequent requests for the same types of data occur without additional hours.





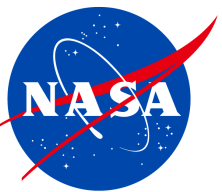
Lightning Assessment and Analysis



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- Define/clarify KSC policy and procedures on facility/system design to assure safety of personnel, flight hardware, and facilities
- Review new facilities designs and existing facilities modifications for lightning protection
- Investigate lightning incidents to determine corrective actions needed including retest of sensitive systems
- Support KSC Lightning Safety Committee
- Interpret data and analyze anomalies from lightning systems
- Formulate/revise lightning safety procedures in ground support documents





Miscellaneous Projects: KaBOOM (Ka-Band Observation: Objects and Monitoring)



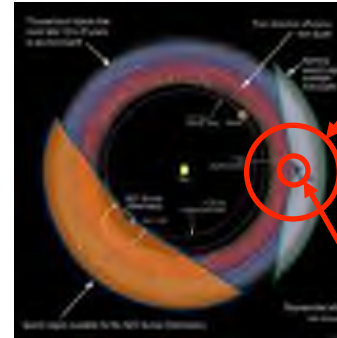
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NASA Primary Goals

Build a high power, high resolution radar system for:

- Precision tracking and characterization of near Earth objects to:
 - Save the Earth from Asteroid impacts
 - Select asteroids for human exploration
- Tracking orbital debris
 - Down to 5 cm at GEO
 - Protect astronauts on the ISS and satellites up to GEO

Orbit determination 100,000 times more precise than by optical means



0.5 AU
capability for
tracking and
characterizing
NEO's

0.1 AU
Current
capability for
tracking and
characterizing
NEO's:

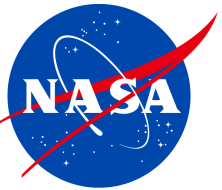
1963



2013



Changes in cataloged objects in orbit around Earth over 50 years



KaBOOM



J. F. Kennedy Space Center

The Demonstration Project

- Phased Array, 3 – 12m diameter antennas
- Eventually operate near 30 GHz
- Main features are the ability:
 - to produce phase-aligned signals at a distant target without external calibration
 - to use a downlink signal (if one is simultaneously present) to measure the effects of tropospheric turbulence along the signal paths and apply real-time corrections to the uplink signal.

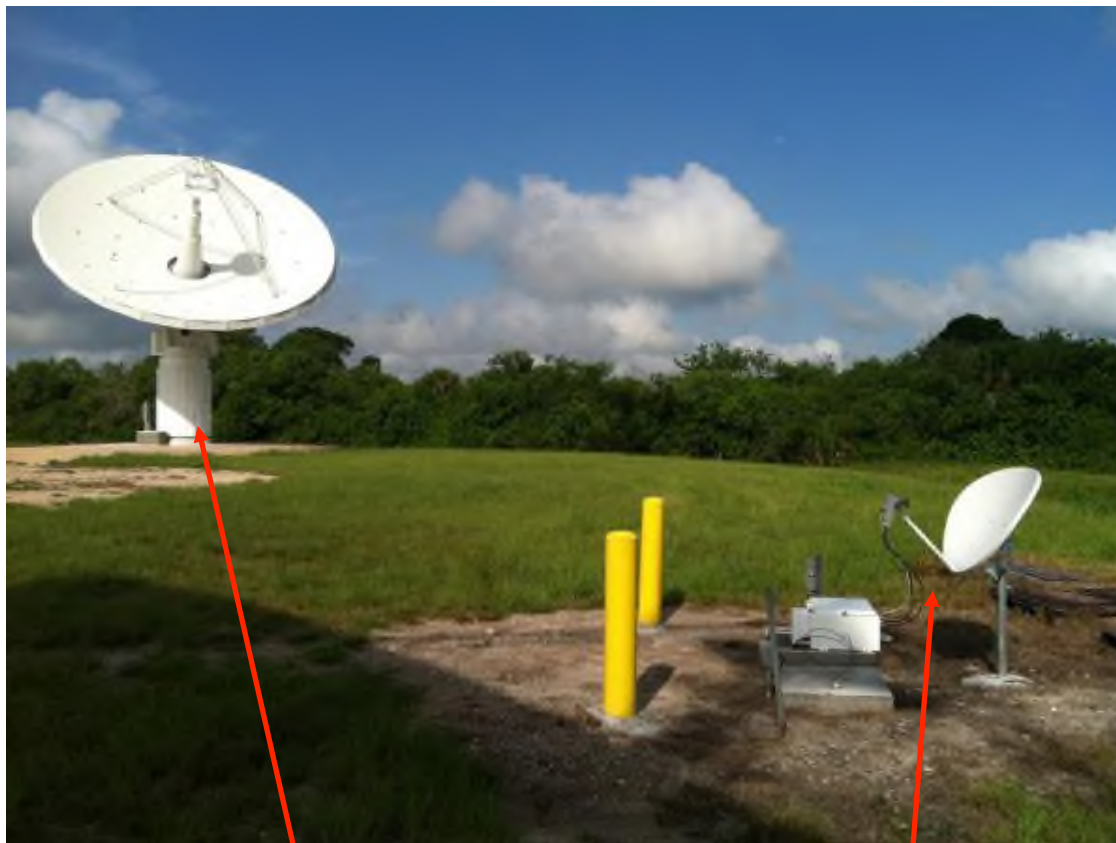




Site Test Interferometers



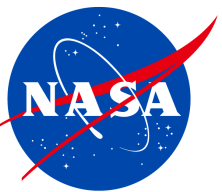
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1 of 3 12 m KaBOOM
antennas

1 of 3 0.8 m Site Test
Interferometer antennas





Site Test Interferometers



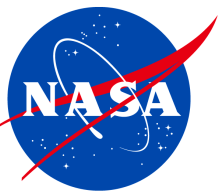
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- An STI constructed by Jet Propulsion Laboratory (JPL) has been implemented at KSC.
- It uses three small antennas to receive signals from a commercial geostationary satellite in order to measure the effects of turbulence in the atmosphere on space communication and radar signals.
- The STI will help KaBOOM determine:
 - how much its signals are being disrupted by the atmosphere, and
 - provide a measure of how well KaBOOM's atmosphere compensation process is working.



Turbulence varies with weather and season, but it is not measurable by ordinary meteorological instruments, hence the need for the specialized STI instrument.





Evolution of Weather Support



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1995

- Government-only launches
- 2-4 launches per month
- 1 Big Customer
- Self-sufficiency Model
- Solely USAF Range
- Upper air data (Balloons only)
- Initial Lightning Launch Commit Criteria (LLCC) development
- Accidents attributed to wx

2015

- Majority commercial launches
- 2-4 launches per month
- Many Med/Small Customers
- Buy-by-the-pound Model
- USAF and FAA-licensed launches
- Upper air data (Balloons, Doppler Radar Wind Profiler (DRWP))
- Gradual refinement of LLCC
- Limited Space Wx assessment
- No recent accidents due to wx

2035

- Government, commercial, tourist launches
- 2-4 launches per week
- Numerous small launches
- Weather funded by commercial users?
- 50% or more Federal Aviation Agency (FAA)-licensed launches
- Upper air data (DRWP, radar, satellite)
- LLCC less conservative & reliant on instrumentation
- Localized, tailored Space Weather evaluation
- Tailored, geolocated wx watches/warnings
- Goal: 0 accidents, reduced scrubs/delays

Effects

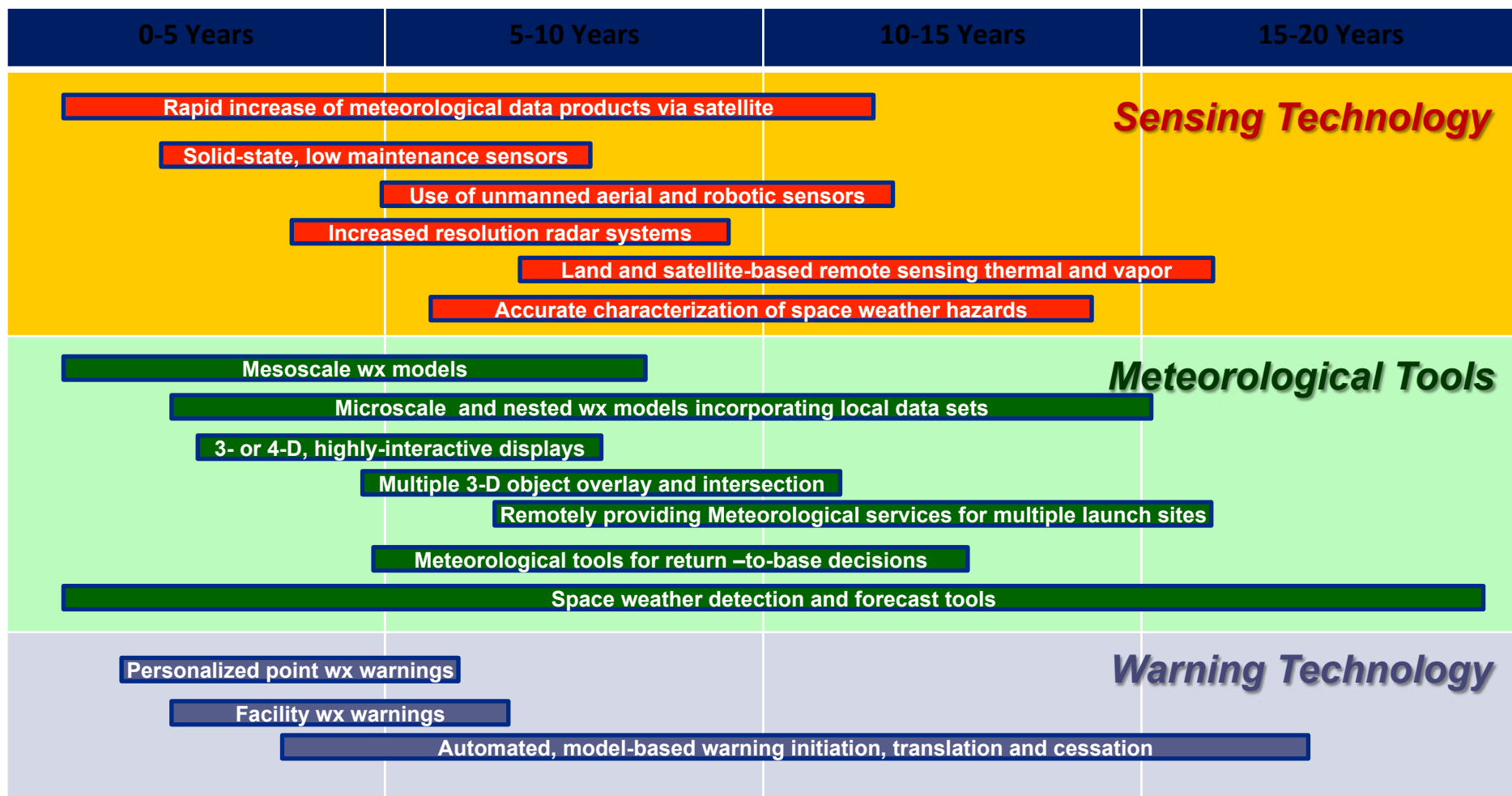
- Reductions (AMU, buoys)
- Complex budget process
- Workforce unfamiliar with state prior to weather incidents
- Continuous demand for increased support for less cost

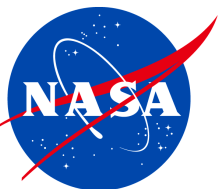


Future Technology in Weather Support



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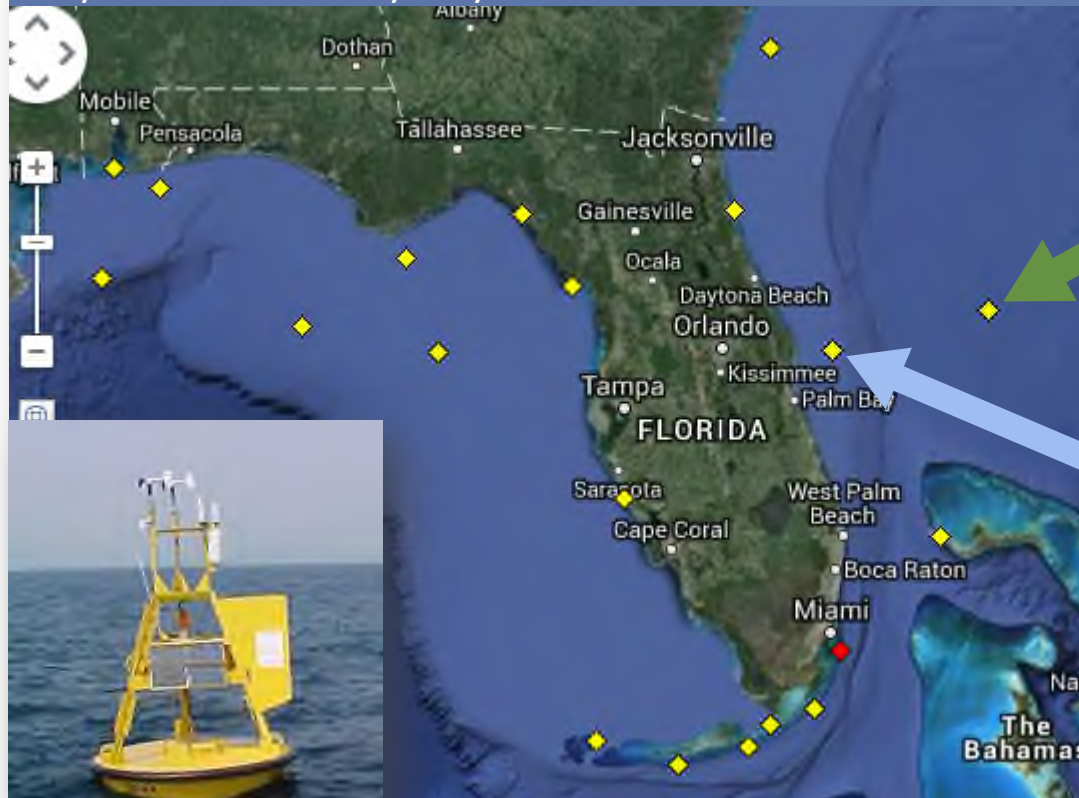


Buoy Update



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NASA no longer funds National Buoy Data Center (NDBC) buoys off KSC and they may be moved at NDBC discretion.



Station 41010 120NM East of Cape Canaveral, FL
3-meter discus buoy

ARES payload

28.903 N 78.464 W (28°54'10" N 78°27'50" W)

Air temp height: 4 m above site elevation

Anemometer height: 5 m above site elevation

Barometer elevation: sea level

Sea temp depth: 1 m below site elevation

Water depth: 1873 m

Station 41009 20 NM East of Cape Canaveral, FL
AMPS payload

3-meter discus buoy

28.522 N 80.188 W (28°31'18" N 80°11'18" W)

Air temp height: 4 m above site elevation

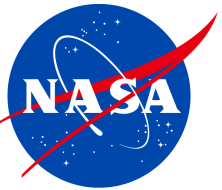
Anemometer height: 5 m above site elevation

Barometer elevation: sea level

Sea temp depth: 1 m below site elevation

Water depth: 40.5 m

Buoys provide data of high integrity and fixed location for which remote sensing capabilities are not available.



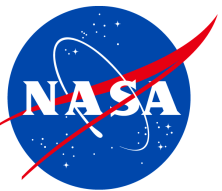
Summary



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KSC Weather:

- Is the result of lessons learned and has a rich history of meteorological research and technology
- Supports numerous activities
- Supports an extensive set of stakeholders, partners and customers
- Has made extensive progress in improving operations availability while ensuring safety



Backup



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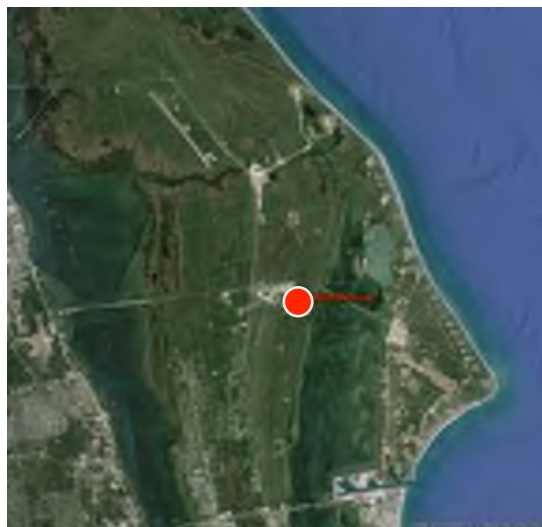
Site Test Interferometers



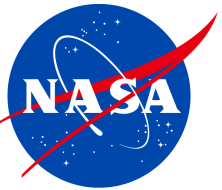
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- The STI will help KaBOOM determine:
 - how much its signals are being disrupted by the atmosphere, and
 - provide a measure of how well KaBOOM's atmosphere compensation process is working.

Location of KaBOOM site at KSC.



Turbulence varies with weather and season, but it is not measurable by ordinary meteorological instruments, hence the need for the specialized STI instrument.

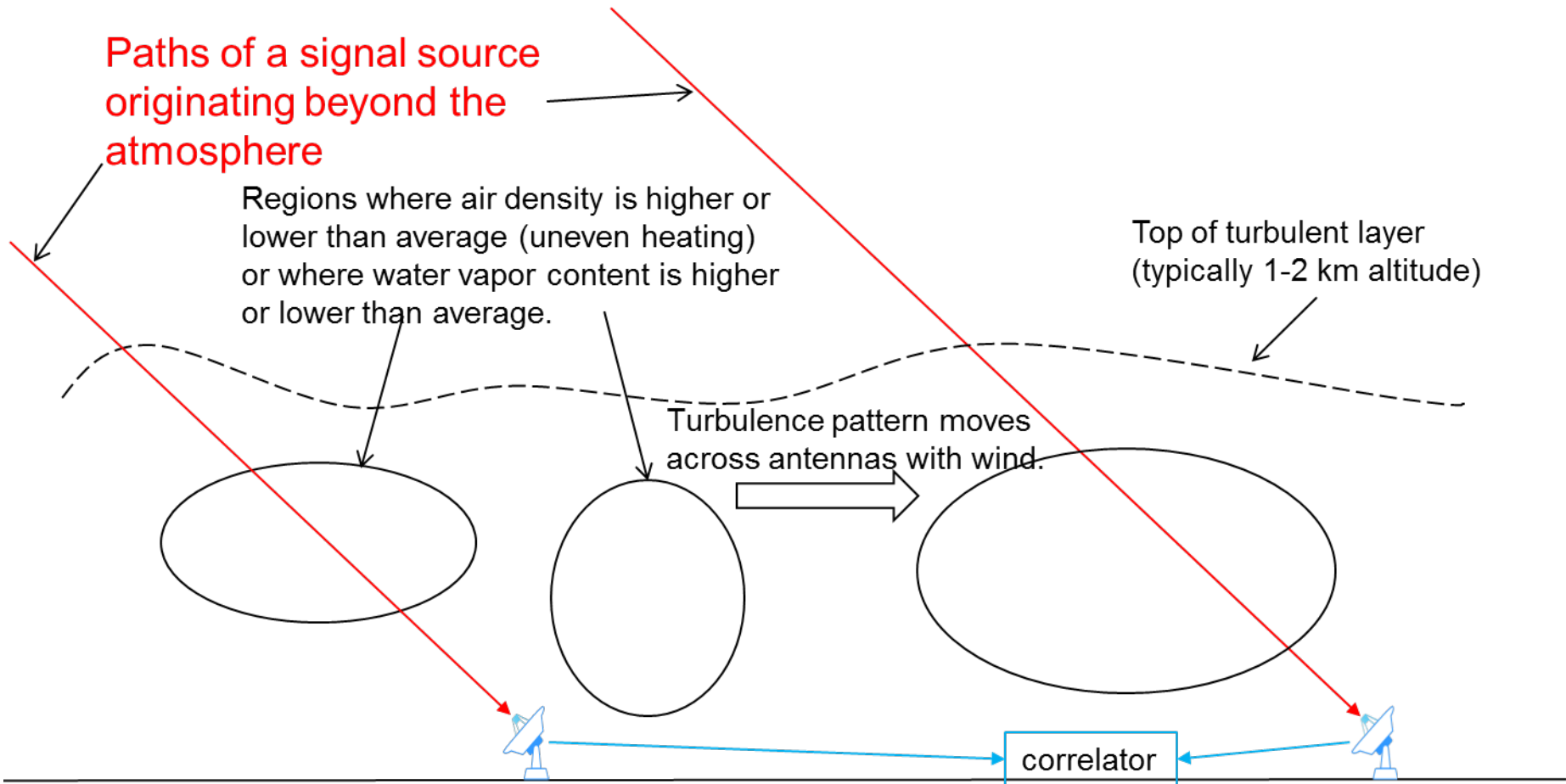


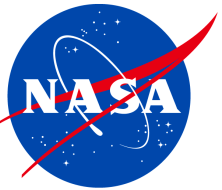
Site Test Interferometers



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Theoretical Background

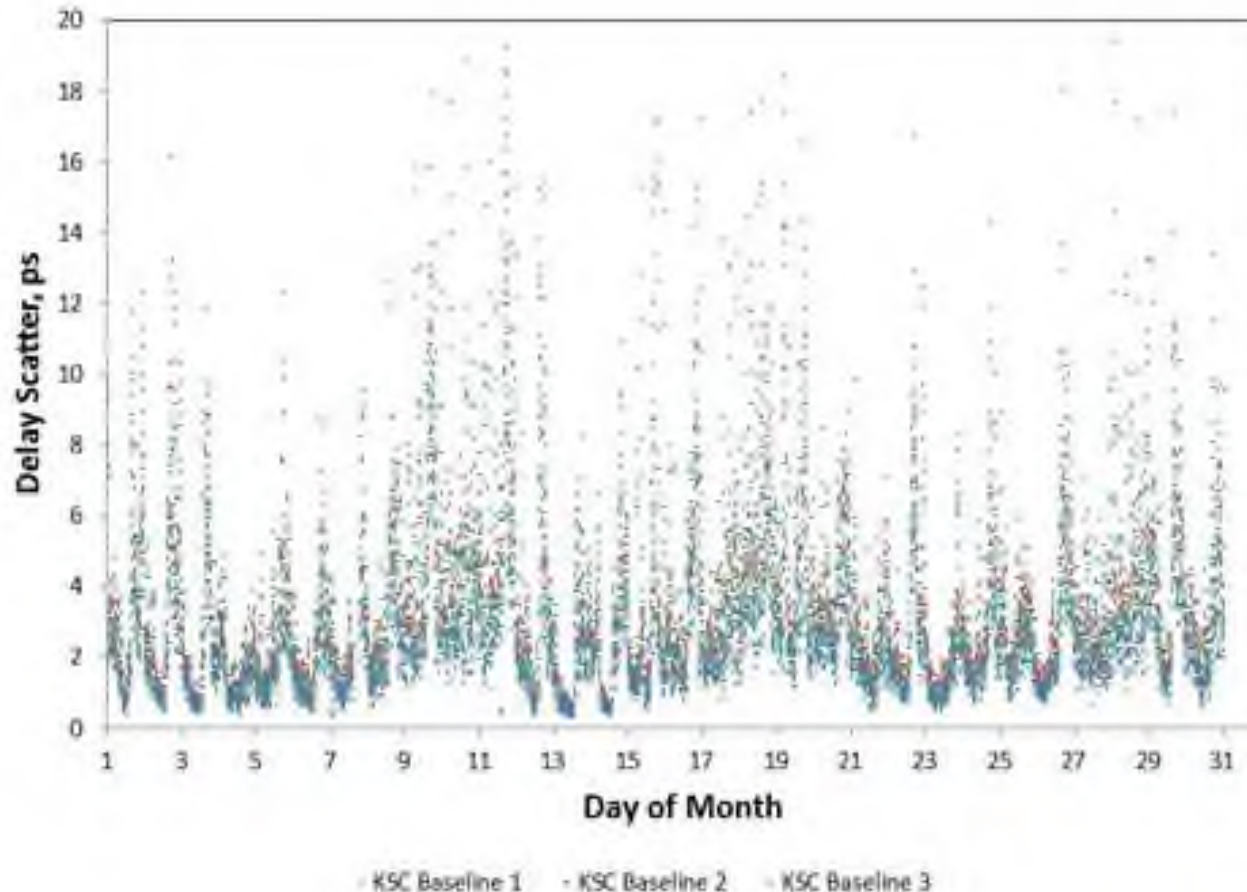




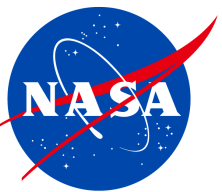
Site Test Interferometers



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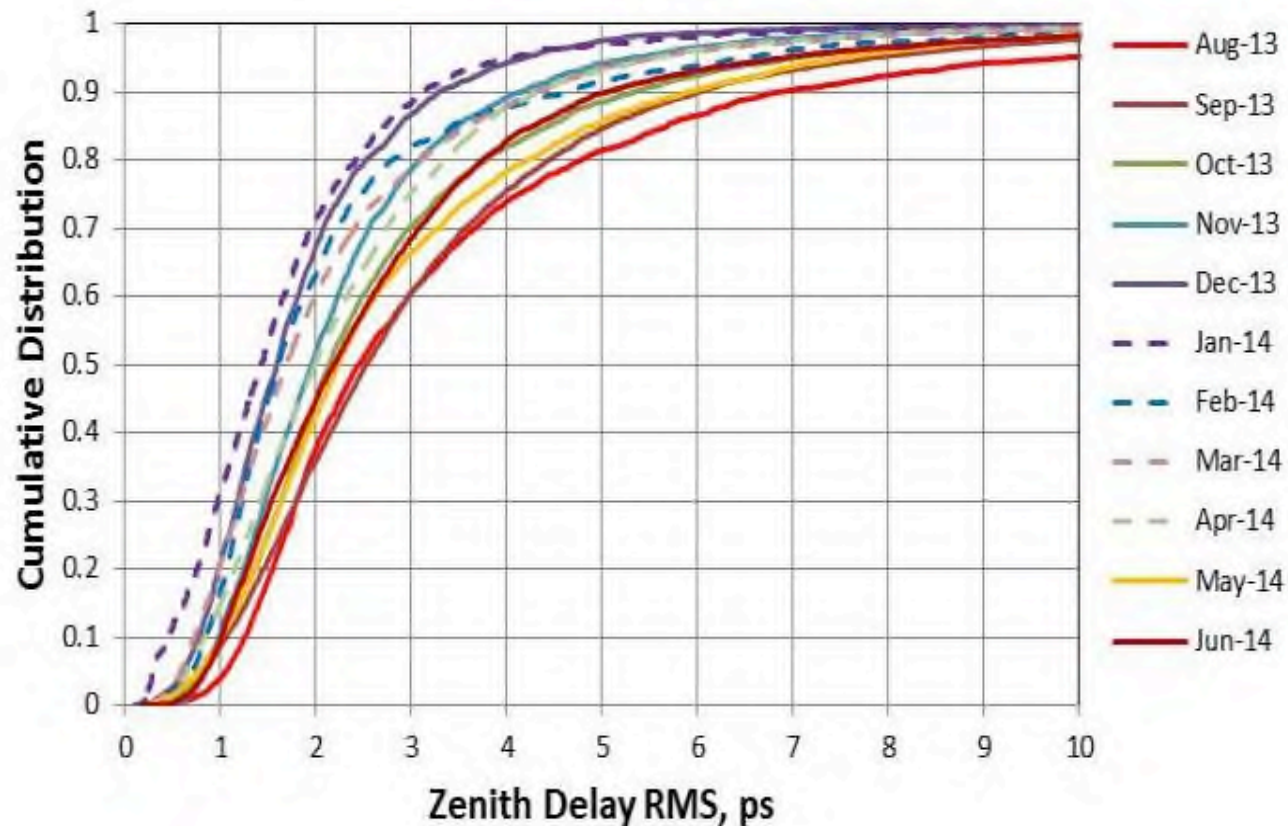
Delay RMS in 600-s blocks referenced to zenith for the KSC STI in September 2013 (all three baselines).



Site Test Interferometers



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Monthly cumulative distribution curves of zenith delay RMS for the KSC STI (warmer months shown in reddish curves, winter months in bluish/purplish curves.)